The Mismanagement of Harmful Algal Blooms: Freshwater and Public Water Systems

by

Kailey Maria Brady

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This essay is submitted

by

Kailey Maria Brady

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and approved by

Essay Advisor: James Peterson, Ph.D., Professor, Environmental and Occupational Health, Graduate School of Public Health, University of Pittsburgh

Essay Reader: Sarah Haig, Ph.D., Assistant Professor, Civil and Environmental Engineering, Graduate School of Public Health, University of Pittsburgh

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Kailey Maria Brady, MPH

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Abstract

Harmful Algal Blooms (HAB) have increased in frequency the last few decades and are a threat to public health. Every state in America has experienced an algal bloom event (Harmful Algal Blooms, 2017). Although there haven't been any human mortalities, there have been human morbidities when cyanobacteria toxins are encountered (Facts about Cyanobacterial 2021). Climate Change is predicted to enhance the duration and number of algal blooms (Recommendations 2015). The Great Lakes, in particular Lake Erie, are at risk to HABs. For example, due to an algal bloom in Toledo, Ohio in 2014, residents were ordered to not drink any of the treated municipal drinking water (Treuer et al, 2021). Furthermore, this water was shut off for three days, costing the community an estimated $65 million in losses (Steffen et al, 2017).

There is no standard treatment process in the United States for treating cyanotoxins in HABs (Treuer et al, 2021). The predicted impact of climate change expects HABs to occur in places that haven't dealt with them before (Moore et al, 2008). This means water management systems will not have allocated adequate money or time to combat a HAB crisis. For instance, water management systems may not budget for HABs in their system since they didn't have issues in the past. They also may not know the best treatment to utilize and because they need to quickly solve the problem, they may choose the wrong treatment inadvertently causing harm. Lysing cyanobacterial cells is a common practice but depending upon where the cyanobacteria produce

the toxin, it could cause an increase in toxin instead of lowering it when the cells are lysed. HABs are an impending public health crisis that need to be taken seriously.

This essay, which is intended to inform the general public along with relevant regulators and stakeholders, will outline the reasons why HABs need to be at the forefront of environmental health policy and public health discussions. HABs are a concern because of their economic burden, their effects on human health, and the lack of a universal treatment process for removing the toxins from water sources.

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1.0 Harmful Algal Bloom Formation and Management

1.1 Introduction and Background

Harmful Algal Blooms (HABs) are created by different types of phytoplankton including *Cyanobacteria*, dinoflagellates, and diatoms (Jones et al, 1999). All three occur in saltwater ecosystems while *Cyanobacteria* are predominant in fresh water. The dinoflagellates and diatoms are associated with what is called red tide because of its distinctive ability to turn water into a red coloration (Harmful Algal Bloom 2017). *Cyanobacteria* are often referred to as blue green algae, because they create green discoloration and thickening of the water they occupy. Sometimes, foul odors are associated with the presence of HABs since some *Cyanobacteria* have the capability of producing a smell (Treuer et al. 2021). But more often than not the smell that is usually associated with HABs is actually from the aquatic biota that are killed when too much *Cyanobacteria* accumulates in the water (McCrackin et al, 2016). HABs cause unwanted physical changes to the water they inhabit, creating dead zones (McCrackin et al, 2016). These dead zones are caused by the phytoplankton utilizing the oxygen and nutrients in the water without leaving any for the other aquatic wildlife (McCrackin et al, 2016). This results in numerous aquatic plants and animals dying at the expense of phytoplankton accumulation.

Beyond just HABs ability to physically alter the environment, they also produce toxins that harm wildlife and human health (Campos et al, 2010). This essay will be focusing on *Cyanobacteria* and the toxins they create. *Cyanobacteria* were chosen since two of the cyanotoxins they create are in the Environmental Protection Agency's (EPA) Drinking Water Health Advisory and because the toxins it creates are more commonly studied. These toxins, called cyanotoxins, are categorized in three groups based upon their different chemical structures. They are, alkaloids, lipopolysaccharides (LPS), and cyclic peptides (Jones et al, 1999).

Alkaloids are toxins that have the ability to target nerve tissue in the brain, cause skin irritation, and/or harm liver function (Hudnell, 2008). This categorizes alkaloids as a neurotoxin, dermatoxin, and hepatotoxin. Focusing on the neurotoxic alkaloids, they have numerous different structures but can generally be described as heterocyclic nitrogenous compounds with a molecular weight less than 1,000 Daltons (Da) (Jones et al, 1999). This essentially means alkaloid toxins are ring like in shape and contain nitrogen somewhere in its structure. Their different chemical structures allow for different chemical by-products to be formed that may or may not be more toxic than the parent compound (Jones et al, 1999). Hepatotoxic alkaloids are also cyclic and have been known to cause serious health problems if found within drinking water (Freitas et al, 2001). When unintentionally ingested, it can cause diarrhea, headaches, and vomiting (Facts about Cyanobacterial, 2021). Also, when a person swims in contaminated water, their skin may encounter dermatoxic alkaloids and the toxins cause skin irritation (Jones et al, 1999). It causes an inflammatory response through protein kinase C activators (Jones et al, 1999). Alkaloid toxins include anatoxin-a and homoanatoxin-a, anatoxin-a(S), and saxitoxins, cylindrospermopsin (Hudnell, 2008).

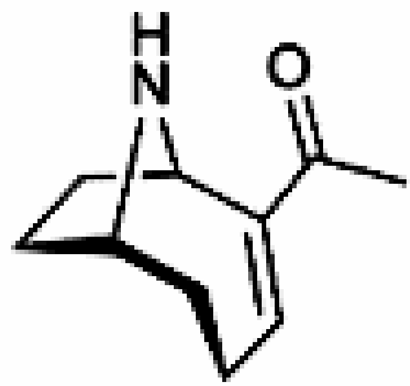

Figure 1. Anatoxin

Anatoxin, a type of neurotoxic alkaloid contains the characteristic carbon-nitrogen bond allowing it to participate in chemical reactions. (Source: "Cyanobacterial Harmful Algal Blooms State of the Science and Research Needs" Accessed 5/22/2022)

LPS is a component housed in the outer membrane wall of Gram-negative bacteria (Hudnell, 2008). This therefore classifies cyanobacteria as a Gram-negative bacteria (Jones et al, 1999). It is a toxin that causes irritation in the body since it doesn't allow the body's detoxification process to operate normally (Hudnell 2008). LPS are comprised of four regions. repeating oligosaccharide units, two regions of an outer core and backbone comprised of polysaccharides, and a glycolipid region that helps stabilize the backbone (Jones et al, 1999). So, when cyanobacteria are lysed open, they could be releasing LPS and cause water to be undrinkable and uninhabitable. However, even their presence without lysing can create harmful interactions since its toxic structure is always exposed to the surrounding water.

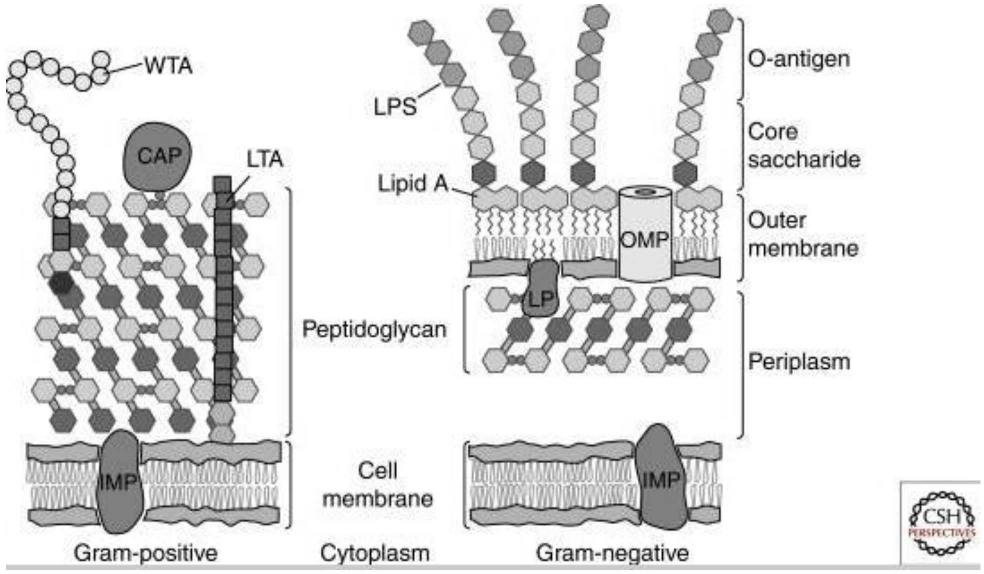

Figure 2. LPS

A generalized structure of LPS in cyanobacteria showing its 4 distinctive regions. (Source: Silhavy, Thomas J et al. “The bacterial cell envelope.” *Cold Spring Harbor perspectives in biology* Accessed 6/16/2022)

Cyclic peptides include the microcystin and nodularin family which are common toxins found within the blooms (Jones et al, 1999). Microcystin toxins are produced by the *Microcystis*, *Anabaena*, *Oscillatoria*, and *Nostoc* genera. Cyclic peptides are typically water soluble and are relatively large in their molecular weight which ranges from 800 to 1,100 Da (Jones et al, 1999). Toxins target the liver categorizing it as a hepatotoxin. Microcystins, which will mainly be focused on in this essay, are part of the cyclic peptide group that contain seven amino acids (Hudnell 2008).

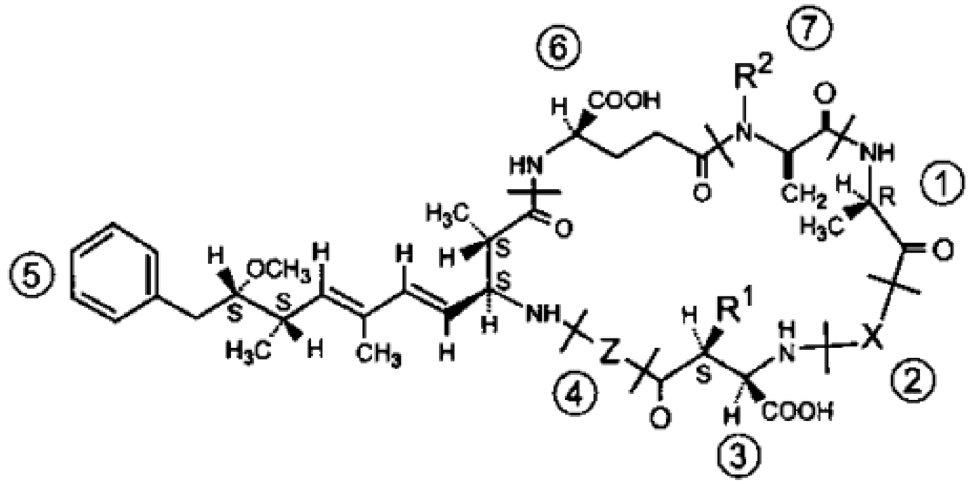

Figure 3. Microcystin

Microcystin, a type of cyclic peptide structure contains 7 amino acids which are labeled above. (Source: Toxic Cyanobacteria in Water: A Guide to Their Public Health Consequences, Monitoring and Management , WHO Accessed 4/8/2022)

Microcystin's unique structure inhibits protein phosphatases that contain the amino acids serine and threonine (Campos et al 2010). Protein phosphatases are crucial enzymes that are necessary for normal function within the body's cells. Microcystin have also been shown to disrupt the mitochondria's normal functions, cause cell apoptosis and affect transcriptional factors and protein kinases that are meant to keep human body cells functioning normally (Campos et al, 2010). The dose of microcystin ingested will determine the severity of the health problems (Campos et al, 2010). Although microcystin toxins have been proven to affect the liver, there is growing evidence of its negative effects on kidney and colon function as well (Campos et al, 2010).

HABs are not just an isolated burden to the United States, they occur worldwide, and they are not a new occurrence in water supplies. In fact, they are naturally occurring molecules in an aquatic ecosystem. However, they have grown more potent in toxicity, greater in concentration, and decay slower in the environment, meaning they overwhelm and damage the aquatic environments they occupy (Gatz 2019). These problems can be attributed to the increasing temperatures from global warming, and nutrient enrichment because of runoff from municipal or agricultural waste (Gatz 2019). Phosphorus is considered to be one of the primary nutrients from run off that spur HAB development (Steffen et al, 2017). Although these two attributes are the main factors that contribute to HABs formation, other factors include light availability, pH, and water circulation (Gatz 2019).

As HABs become more common there is greater chance for humans to be exposed to toxins. The Centers for Disease Control and Prevention (CDC) released illnesses associated with exposure to these toxins the cyanobacteria create which are outlined in Table 1.

Most of the illnesses outlined in Table 1 are from acute exposure, however humans are more likely to be exposed to cyanotoxins through chronic exposure (Campos et al, 2010). Chronic exposure can be linked to tumors, cancer, and liver diseases (Campos et al, 2010).

There have been numerous fatalities in animal species including dogs, cattle, birds, and fish to name a few (Bláha et al, 2009). Although there have not been direct mortalities in humans associated with HAB exposure, the long list of morbidities makes it a public health concern. Especially with the most concerning exposure being liver failure in dialysis patients that received contaminated water containing microcystins during treatment (Facts about Cyanobacterial, 2021).

Table 1. HAB Exposure

Cyanobacterial Harmful Algal Blooms	
Exposure Route	Symptoms
Ingestion	Nausea, vomiting, diarrhea, mild liver enzyme elevations, conjunctivitis, rhinitis, earache, sore throat, swollen lips, atypical pneumonia, hay fever-like syndrome, electrolyte imbalances, headache, malaise, muscle weakness, pain in joints and limbs.
Inhalation	Rhinitis, sore throat, bronchospasm, pneumonia
Skin Contact	Dermatitis, perioral blisters
Eye Exposure	Conjunctivitis, lacrimation, swelling, photophobia

Signs and symptoms associated with cyanobacterial HAB exposure. Created using data from “Facts about Cyanobacterial Harmful Algal Blooms for Poison Center Professionals.” Accessed 1/18/2022.

HABs are a growing threat to the environment and human health. With the persistence of the HABs in freshwater, there is a concern that drinking water treatment facilities will not be able to remove the toxins and hence ensure the water is safe for human consumption (Treuer et al, 2021). However, the nature of HABs is still only partially understood because of their irregular occurrence and the lack of monitoring in large bodies of water (Treuer et al, 2021).

The greatest concern however is that drinking water systems do not have clear or standardized protocols in place to effectively manage and treat waters contaminated with cyanotoxins (Treuer 2021). The EPA released recommendations for managing cyanotoxins in public drinking water; however, numerous times throughout the document it is mentioned that “this document is not a regulation; it is not legally enforceable” (Recommendations, 2015). The EPA also does not recognize microcystins or cylindrospermopsin as contaminants under the Safe Drinking Water Act. However, it is promising that the EPA published the Draft Fifth Contaminant Candidate List which includes numerous cyanotoxins. This means that cyanotoxins have the potential to be further regulated under the Safe Drinking Water Act but it could take numerous years to make it on that list.

An analysis done by the Intergovernmental Oceanographic Commission examined approximately 9,500 HABs over the past 33 years (Hallegraeff et al. 2021). HAB they found have generally increased in Central American, South America, Mediterranean, and North Asia (Hallegraeff et al. 2021). Although some areas did not show significant change such as East Coast America, South East Asia, and Europe this doesn't mean that areas without significant change should be lax or ignored (Hallegraeff et al. 2021). This study only accounts for the number of HAB events with corrections for increased monitoring and does not look at other factors such as increased duration (Hallegraeff et al. 2021). The rising annual global temperatures means an increase in the duration and increased range of HABs due to a prolonged growth period (Moore et al, 2008). This is because HABs thrive in warm aquatic ecosystems (Gatz 2019). Although algae and other phytoplankton are a natural part of ecosystems, the increased abundance, duration, and range of HABs is a concern (Gatz 2019). When these large algal blooms begin to decompose, they will exhaust oxygen within the ecosystem they occupy (Gatz 2019). When there is no longer oxygen in the water, it creates a hypoxic environment (Andersen 2009). Dead zones are hypoxic regions where numerous fish and invertebrates will die at the expense of increased phytoplankton number (McCrackin et al, 2016).

Although there have been more strides in monitoring there are still unknowns in understanding the future behavior of HABs. HAB have become more than just a rare nuisance for the environment to deal with, they are now a more persistent problem that needs better monitoring efforts.

1.2 Climate Change's Impact on HABs

Climate change is associate with an increased concentration of carbon dioxide in the atmosphere and an increase in average temperature. (Gatz 2019). These two consequences of climate change have been linked to HABs increased presence on a global scale because climate change creates favorable conditions for eutrophication to occur in water systems (Andersen 2009).

For instance, an increase in carbon dioxide creates a favorable environment for phytoplankton to flourish because of its use in photosynthesis (Moore et al, 2008). Therefore, more carbon dioxide present in the water, the greater the opportunity for HABs to grow since it is the phytoplankton's source of energy. As HABs expand in biomass they can form large thick blankets which prevent sunlight from penetrating into the water and can cause a reduction in biodiversity and in severe situations lead to hypoxic water or dead zones (Gatz 2019 & Andersen 2009). Figure 4 illustrates the large range of HABs within the Ohio River. This HAB event extended 650 miles of the river passing through four states (U.S. EPA Office of Water). There was a recreational advisory in place so that no adverse human health effects would occur (U.S. EPA Office of Water).

Eutrophication can be described as "an increase in the supply of organic matter to an ecosystem rather than as a simple problem of nutrient pollution" (Anderson 2009). Hypoxia is a part of the eutrophication process and the dead zones' presence has expanded more than 245,000 km^2 globally (Andersen 2009 & McCrackin et al, 2016). When these eutrophication events occur, it is difficult to determine when they will recover to pre-eutrophic conditions (McCrackin et al, 2016). Although there are not many long-term monitoring systems in place, it has been estimated to take 25 years or longer for aquatic ecosystem to recover from a eutrophic event (McCrackin et al, 2016).

Research is still new in this area and more monitoring is necessary to better understand the association between climate change and HAB. However, there is a strong connection between the two that warrants attention. If water managers are able to understand a typical pattern for when HAB will occur in their area, they can better prepare for outbreaks or expect prolonged eutrophication events.

Figure 4. Ohio River

The Ohio River experienced a HAB that lasted from August until October 2015 that spanned 650 miles. It passed through Ohio, West Virginia, Kentucky and Indiana. (Source: Water, U.S. EPA Office of. "Tracking Cyanohabs." Accessed 6/17/2022)

1.3 HABs in Drinking Water

Cyanotoxins created by HABs are regulated differently in each state with their own choice of guidance values for each type of cyanotoxin (Henrie et al, 2017). At the federal level, there are no hard-set regulations, only Health Advisories (HAs) are given to the states to determine what it is they should do with the HABs and their toxins (Henrie et al, 2017). The EPA sets their HA limit for Cylindrospermopsin as 0.7µg/L for bottle-fed infants and pre-school children and 3.0µg/L for school-age children and adults. The HA limit for Microcystins is 0.3µg/L for bottle-fed infants and pre-school children and 1.6µg/L for school-age children and adults. Again, this means that although these are limits for two cyanotoxins that the government has found to be acceptable, states could choose to adhere or ignore these levels unless the state takes it upon itself to create rules. Ohio, for instance has more conservative limits for cyanotoxins and includes two more cyanotoxin limits, anatoxin and saxitoxins, in their list (Dewine, 2020).

States that are affected by HAB, like Ohio, should require monitoring for *Cyanobacteria*. Specifically, this requirement would be for public water systems that utilize surface water as their main water source. Groundwater and flowing surface water such as rivers are not likely to accumulate cyanotoxins since groundwater does not have sunlight the *Cyanobacteria* need to survive and flowing water typically is unfavorable for high accumulation of *Cyanobacteria*. It is not feasible for every public water system to prepare for HAB if their water sources are not likely to be affected by them. But, those public water systems that are at risk of a HAB event should create specialized rules based upon the USEPA's "Recommendation for Public Water Systems to Manage Cyanotoxins in Drinking Water" just as Ohio has done.

HABs are projected to increase in occurrence and magnitude, yet there is very minimal evidence that water treatment plants are prepared for contamination by cyanotoxins (Treuer et al, 2021). Often times water managers rely on the color change that HABs create to determine if it is present in their water supply (Treuer et al. 2021). However, cyanotoxins can be in a water source without showing the distinctive green discoloration and odor (Treuer et al, 2021). Without the distinctive physical signs, most water management plants cannot detect if toxins are present and could inadvertently expose the population to harmful cyanotoxins (Treuer et al, 2021).

Once the toxin is determined to be in the water, it is difficult to remove it. Depending upon what cyanotoxin is present will determine how effectively it can be removed from the system. One of the treatments to remove cyanotoxins is by lysing the cyanobacterial cells (Treuer et al, 2021). However, this could initially release the toxins that were stored inside the cells temporarily causing increased toxin levels in the water (Treuer et al, 2021). In fact, during the Toledo water crisis in 2014, the microcystin cells were lysed open allowing the toxin to be released into the water creating a large dispersion throughout the water system (Steffen et al, 2017).

Another common way to remove the toxins is by using heavy chlorination treatments to try to disinfect the water. When free chlorine is added to a system, it is helpful in removing cylindrospermopsin and saxitoxin but will not clear anatoxin from the system (Cyanobacteria and Cyanotoxins, 2019). Chlorination is a normal step in the treatment process. But the amount necessary to be effective is not typically justified for drinking water treatment (Cyanobacteria and Cyanotoxins, 2019). An added dechlorination step is necessary to create potable water for the public.

In Treuer's article, 355 managers of water treatment plants completed a survey about HABs. Results from this survey suggest that the management systems that have experienced Toxic Algal Blooms (TAB) become self-reliant utilizing knowledge from their own experiences and are less likely to seek external aid from other sources. Self-isolation will delay helpful information and cause the detriment of the community the water treatment plant serves

What Treuer's article means about self-isolation is that when water management systems solve problems on their own, they start to believe that their solution is the best and possibly the only solution. This is most likely because the resources available to them did not provide answers to their problems. So, when new information becomes available that is helpful, water manager may not think to seek out or utilize these resources because in the past, it wasn’t helpful to their particular circumstance.

They also found in this survey that in water systems that have not experienced TABs, the managers do not consider them to be a major issue and naively think they would be easy to manage. This could lead to a false sense of security for treatment plants that utilize local surface water sources. The removal of cyanotoxins is expensive and since it is not a criteria pollutant, most water management facilities would not include its management as part of their normal budget (Recommendations 2015). Also, since there are not any set regulations, water management facilities do not have actual laws to turn to and cannot easily find relative standards for cyanotoxins (Recommendations 2015).

An ecophysiological examination of the Toledo Crisis of 2014 suggests that the toxic bloom was a “common bloom scenario” based upon the standard cyanobacterial index but the water system was unprepared causing 400,000 residents to be without potable water (Steffen et al 2017). They also mention that there is a strong chance that this type of scenario could happen again (Steffen et al, 2017). It is up to the water management system to set a strategy in place without the aid of the federal government and ensure that conditions of Lake Erie do not worsen leading to increased chance of eutrophication. If the Toledo Crisis of 2014 was a typical scenario, then other water management systems will be woefully unprepared if they haven’t experienced one before as HABs are likely to increase in occurrence and in places they haven’t occurred before.

2.0 Public Health Significance of Algal Blooms

2.1 Human Health

People are exposed to HABs through numerous routes. There is dermal, inhalation, oral and an intravenous route through contaminated dialysis equipment (Freitas et al, 2001). There could be incidental ingestion of cyanotoxins by swimming in contaminated water bodies, but humans will be primarily exposed to cyanotoxin through the ingestion of drinking water. Although the main chance of exposure is through drinking water, it is also important to look at the consumption of animals and plants that have accumulated the toxin (Dziga et al 2013, Freitas et al 2001, Xiang et al 2019).

A three-year study reported in 2001 investigated microcystin exposure of fish in the Jacarepagua Lagoon (Freitas et al, 2001). Monitoring the blooms that naturally occur and the fish's subsequent body concentrations of the cyanobacteria/microcystin by analyzing tissue samples (Freitas et al, 2001). The fish were exposed through oral ingestion of the cyanobacteria and the results showed that even when the blooms decreased the toxin remained in the fish muscles and livers (Freitas et al, 2001). Although most fish did not die, the study did show that the fish accumulated microcystin to the point that "71.7% of the muscle samples were above the recommended tolerable daily intake" (Freitas et al, 2001).

This bioaccumulation of microcystin in animals is concerning for people who eat any form of meat or animals higher in the food chain. Bioaccumulation is the process where contaminants like microcystin, or other harmful chemicals like pesticides, remain for long periods of time in the body that can cause adverse health effects. When too much of a toxic chemical is stored inside the body, it cannot be processed naturally and will have compounding harmful effects. Essentially, the toxin that was being stored inside the fish's body will be transferred to the human who ingested it causing high levels of toxins to enter the body.

Another experiment which was carried out in 2019 throughout southern China investigated microcystin concentration in crops that were irrigated with microcystin contaminated water (Xiang et al, 2019). Microcystin can be introduced to agricultural fields when irrigated with polluted water or when fields are fertilized with cyanobacterial blooms called green manure (Xiang et al, 2019). Not only is persistence within the agricultural produce a problem, but the microcystin toxin can also stay in the soil for numerous weeks (Xiang et al, 2019). The scientists found that microcystin permeated inside the crops after irrigation and the concentration exceeded the WHO's reference dose of 0.04 µg/kg*day (Xiang et al, 2019).

Many people do not consider HABs to be a significant public health problem because most eutrophication events are short lived. However, the toxin persists in the animals and vegetables humans consume. And depending upon how serious the eutrophication event, the longer it may take for these bodies of water to return to normal status, even after the eutrophication event itself has ceased (McCrackin et al, 2016).

Microcystins are toxic to the human liver. One major way it achieves toxicity is through the activation of the Nuclear erythroid 2-related factor 2 (Nrf2) pathway in the liver (Lundqvist et al, 2017). Nrf2, is a highly important regulator for the protection of cellular function but it is not meant to be utilized as an everyday normal function of the body (Xu et al, 2019). When the Nrf2 pathway is activated, it is an indication that there is oxidative stress on the liver (Lundqvist et al, 2017). The activation of this oxidative stress and inflammation are two key factors that can lead to liver disease (Xu et al, 2019). Although this is meant to be a protective pathway for the body to detoxify toxins, its activity may be too great and the pathway can be overwhelmed (Lundqvist et al, 2017). Microcystin can cause acute liver injury and even be considered a carcinogen because of their ability to cause oxidative stress on the liver (Lundqvist et al, 2017 & Xu et al,2019). In fact, the International Agency for Research Cancer classifies microcystin-LF as having the potential to be a carcinogen to humans, however the EPA does not acknowledge this statement (Lundqvist et al, 2017).

2.2 Economic Burden

HABs occur worldwide and the United States alone spends 2.2-4.6 Billion dollars a year to combat the problems that come with them (Treuer et al, 2021). Algal blooms are not just an economic burden to the United States. England and Wales have also experienced the economic burden of eutrophication events and spend the equivalent of about 105-160 million dollars every year (Pretty et al, 2003). If federally recognized as an environmental contaminant in drinking water, and thus a threat to human health, this problem could be better managed with preventive action instead of incurring drastic costs in cleaning up the algal bloom messes that were created.

Numerous studies and government opinion agree that monitoring is one of the most important ways to understand and mitigate eutrophication events, yet there isn't much funding for it and most water management sites don't put financial resources into something that is not regulated by the government (Treuer et al, 2021, Recommendations 2015, Steffen et al 2017). By understanding toxic blooms and investing money in prevention, mitigation strategies could be created to better handle the situation (Steffen et al, 2017). Because Toledo was unprepared during the 2014 water crisis, it is estimated to have cost the community $65 million in economic losses from local businesses, industries, and community members (Steffen et al, 2017). HABs cause economic burden for fisheries, tourism, and lower waterfront property values (McCrackin et al, 2016).

Instead of spending billions of dollars in reactive measures, places like Florida Atlantic University were awarded 2.2 million dollars to monitor the algal blooms that appear in the 730 square miles of Lake Okeechobee (Galoustian, 2020). The grant to fund this was awarded by Florida's Department of Environmental Protection (Galoustian, 2020). It is promising that a State is investing in monitoring, but the federal government does not have the same drive to understand and mitigate bloom events. By investing in prevention, communities can avoid the larger economic burden that clean-up and reactive strategies pose.

2.3 Environmental Health

For freshwater ecosystems, eutrophication is a major stress factor (McCrackin et al, 2016). When cyanobacteria create dead zones, it causes fish mortality and morbidity, and the fish that do survive have lower reproductive success in the future (McCrackin et al, 2016). Hypoxic water body counts have "increased 30-fold since the 1960's" (Harmful Algal Blooms, 2017). Another contributing factor to the increased number of blooms is from water transportation utilizing ballast water (Recommendations, 2015). If cyanobacteria are producing toxins in a water source that is taken up in the ballast of a ship and transported to another location, that new water source is now contaminated with cyanobacteria that wouldn't have been present in the first place (Recommendations, 2015).

In a three-year study done by Freitas *et al*., they followed aquatic life from the Jacarepagua Lagoon in Brazil. They looked at numerous species of fish along with Phytoplankton. Their study suggests that microcystin can accumulate in these species because even in times of low water bloom densities, the fish tissue from the harvested organisms contained concentration close to or above the recommended limit for human consumption at 0.04 $\mu g\ kg^{-1}$ day. For communities that utilize fish in these water bodies, eating fish for multiple meals could mean surpassing the limit of exposure to microcystin for human consumption.

In a meta-analysis done by McCrackin *et al*. 89 studies were analyzed to better understand water recovery after a eutrophication event. Although the study pointed to some general trends, it still emphasizes that much about eutrophication events are unknown and the pattern it follows and factors that create harmful events is not well understood. They found that most recovery is multi-decadal to reach the baseline levels of water sources before the eutrophication event took place. They further discuss that a 25 year recovery period is needed, assuming that another event does not occur while it attempts to recover. They did find that when contamination from excess nutrients, such as agricultural run-off, decreases then algal abundance and growth rates would decrease causing water clarity would improve. Even though this water clarity is an immediate and helpful change to the water source, it does not mean in the long term it will recover quickly. McCrackin et al. found that there was no significant difference in recovery time to pre-eutrophic conditions when comparing water bodies with partial reduction of added nutrients compared to those with complete reduction of added nutrients. Just because clarity is achieved faster does not mean it will be the fastest to recover completely. This leads to the idea that eutrophication events are multifaceted and that although factors have been identified about them, there is more to understand about their nature and how to better combat the issue.

3.0 Water Management of HABs

3.1 Current Guidelines for Managing HABs

As it currently stands, there are no federal regulations for cyanotoxins under the U.S. Safe Drinking Water Act (SDWA). Advisories have been developed to aid water managers in combating HAB in public drinking water, but they are not enforceable and do not need to be adopted. Although cyanotoxins are not part of the SDWA, they are currently on the Fourth Unregulated Contaminant Monitoring Rule (UCMR). This took place from 2018-2020 that monitored 30 chemical contaminants to which they included 10 cyanotoxins. The UCMR is meant to gather information about the contaminants on the list which would then be used to "develop regulatory decisions" and potentially be added to the contaminants under the SDWA (Recommendations 2015).

But there are two encouraging aspects of regulation. The first encouraging part about cyanotoxins being a part of the UCMR is that any public water system that serves more than 10,000 people must collect finished water samples for cylindrospermopsin, microcystins, and anatoxin-a analysis. Even though this does not include raw water sampling it is an important component to keeping the public safe from cyanotoxins in their finished supply. The second is that the EPA published the Draft Fifth Contaminant Candidate List which includes numerous cyanotoxins. This means that cyanotoxins have the potential to be further regulated under the SDWA but it could take numerous years to make it on the SDWA list. This is just a draft, but it means that cyanotoxins has moved further in the process to eventually become a criteria pollutant under the SDWA..

Even without being a recognized drinking water contaminant, the government recognizes the harmful toxins HAB contain and created the Harmful Algal Bloom and Hypoxia Research and Control Act (HABHRCA). Back in 1998, Congress created the HABHRCA to better understand and monitor HAB and predict when these events will occur. Along with that, the CDC created the One Health Harmful Algal Bloom System (OHHABS). The OHHABS was created in 2016 to address environmental and public health problems associated with HABs. A voluntary program, state and local health departments can report to them about illnesses and environmental data.

The government recognizes the need to investigate cyanotoxins and create appropriate advisories, but cyanotoxins have, so far, not been added to the list of contaminants under the SDWA. Because the issue is not officially recognized, any relevant advisories created cannot be enforced by water management agencies and some are hesitant to utilize the advisories for fear of legal repercussions (Henrie et al, 2017).

3.2 Management of HAB in Drinking Water

After the EPA released the Health Advisory for cyanotoxins, they released along with it a management tool for public water systems to utilize in order "to assist them as they consider whether and how to manage cyanobacterial toxins in drinking water" (Recommendations, 2015). Even though there are numerous different cyanotoxins, the document only includes strategies on dealing with microcystin and cylindrospermopsin. Although these are the more common toxins of concern in water management, it is arguably too limited; for instance, there is no information on how to respond to cyanotoxins in recreational waters.

The Recommendations document does however create a model containing five management steps (Figure 5):

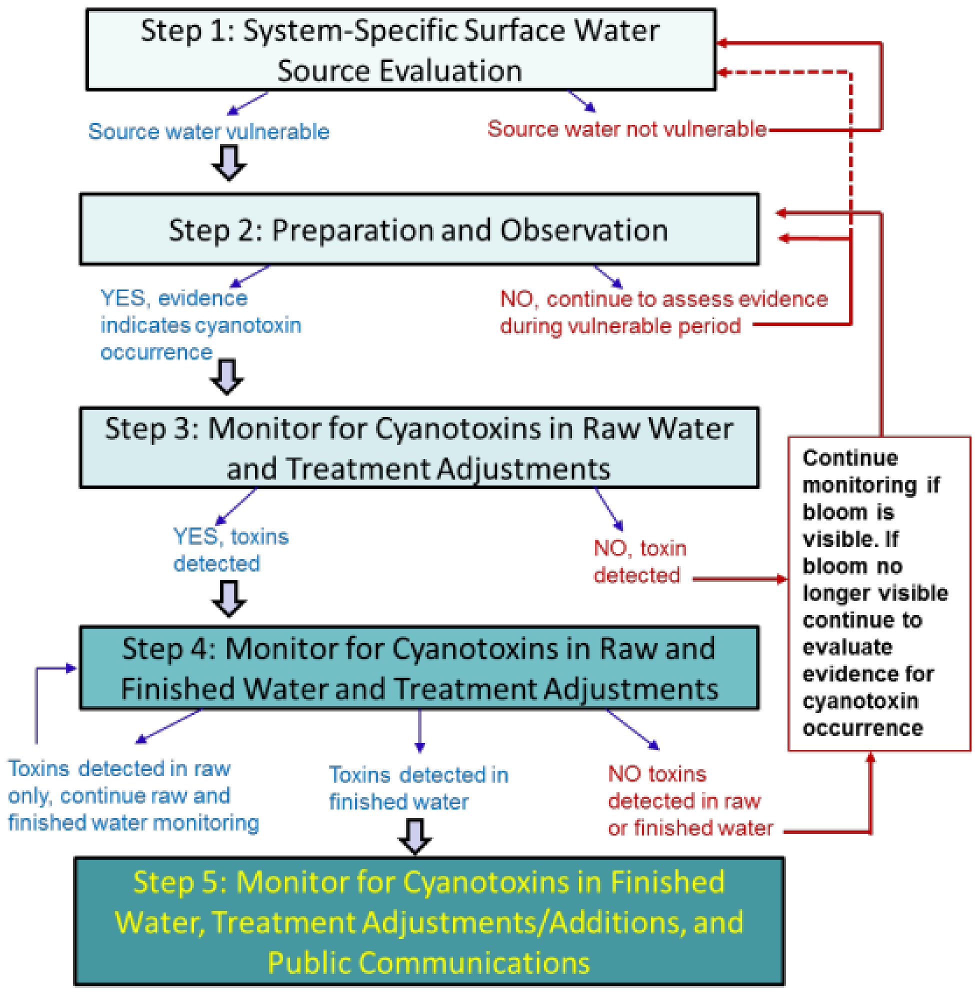

Figure 5. Federal EPA Cyanotoxin Management Steps

This figure shows the generalized scheme water managers should follow in treating their water systems that contain Cyanotoxins. (Source: Recommendations for Public Water Systems to Manage Cyanotoxins in Drinking Water Accessed 01/25/2022)

The steps follow the general scheme that, if further investigation is not deemed necessary, then the public water system does not have to continue to the subsequent steps. For example, if the water manager does not feel cyanotoxins are a threat to their water supply they do not have to continue to step two and the rest of the document is not utilized.

Although these steps are at least a start toward a working foundation that all water management systems should utilize, the document again emphasizes that it “is not a regulation” and “is not legally enforceable.” Since these toxins are not seen as something in need of enforcement, water management systems who have never dealt with HABs may see this process as a waste of resources and not utilize the recommendations. With the frequency of blooms increasing, it is only a matter of time until more water management places deal with this problem that they are ill prepared for. It also explains that the “EPA does not currently regulate cyanotoxins and Public Water Systems are not required to monitor for cyanotoxins in their drinking water (unless required by their primary agencies)” (Regulations, 2015).

3.2.1 Step One: Conduct System-Specific Surface Water Evaluations

The first step in this document entitled *Recommendations for Public Water Systems to Manage Cyanotoxins in Drinking Water* is to determine vulnerabilities within the system or factors surrounding it that could cause contamination. These factors include the source water that the public water system utilizes. Public water managers need to look at whether their water source is ground water or surface water since ground water sources do not typically contain cyanotoxins. Surface water that comes from rivers or flowing water is also less likely to accumulate cyanotoxins. This step is also to look at the history of the public water system to see if there have been blooms in the past or if there are high levels of nitrogen and/or phosphorus which are typically factors that contribute to a HAB. Water managers are also encouraged to look at land use surrounding their watershed along with typical climate and weather information for their area.

3.2.2 Step Two: Preparation and Observation

If the public water system determines after the first step it is vulnerable to cyanotoxin presence, then the manager can move on to step two to prepare and observe for potential HAB. This step is very similar to step one except water managers take a more active role in observing the water source. Managers now look to the seasonality of the blooms that could occur. If cyanotoxin presence is consistent then the EPA suggests to install a permanent treatment of their choice. This step also contains suggestions to inspect the source water. They only list visual inspection and typical system indicators to look for if cyanotoxins are present. But, they do list the following potential treatments. They include ultrasonic treatment, algaecides, coagulants, skimming, and aeration. However, these treatments should not be started until samples are taken in step three.

3.2.3 Step Three: Monitor for Cyanotoxins in Raw Water and Treatment Adjustments

When the public water system determines that there is a presence of cyanotoxin through "visual inspection, system effects, or other bloom indicators" from step two, water managers should then sample the raw water source for cyanotoxins. If sampling shows cyanotoxin presence, water managers need to determine if the toxin is intracellular or extracellular. If the cyanobacterial cell contains the toxin intracellularly then the toxin is produced and contained within the cells. They toxin is released when the cell dies or if the cell is lysed open. Extracellular on the other hand can release toxins throughout their lifecycle and not have to be released only through cell death.

Once the type of cyanobacterial cells is determined, treatment options need to be decided. The EPA recommends four treatment strategies. They are removing intact cells, minimizing preoxidation of raw water, adding or increasing powdered activated carbon, and lastly increasing post-chlorination. However, the water manager needs to determine which treatment is the best option to first try based upon treatment goals and operational issues they are experiencing. It is important to determine whether the cells are intracellular or extracellular because if the treatment lyses cells that contain the toxin intracellularly, it will increase the concentration of cyanotoxin in the surrounding water, instead of lowering it.

3.2.4 Step 4: Monitor for Cyanotoxins in Raw and Finished Water and Treatment Adjustments

When cyanotoxins are found in the raw water then the water managers are suggested to move to step four where the EPA suggests they now monitor raw water and finished water too. The raw and finished water should be sampled "two to three times per week until cyanotoxins are no longer found in the raw water." As sampling and treatments continue, if cyanotoxins are found in the finished water then the water system will move to the final step, step five, of the process. The presence of cyanotoxins in finished water means that the treatment being utilized was not enough to contain it to the raw water. Once it is in the finished water, the chances of the toxin ending up in household tap water increases.

3.2.5 Step 5: Monitor for Cyanotoxins in Finished Water, Treatment Adjustments or Additions, and Public Communications

When cyanotoxins are detected in finished water, the water management system can move on to step five of the process. The EPA suggests water managers to communicate the findings to state, local and public health officials. Step five contains a monitoring response that has three levels. Low, Medium, and High Level. It explains the suggested communication, treatment actions, and monitoring response for each level of cyanotoxin presence in finished water. However, for treatment actions it doesn't recommend which treatment to utilize it just mentions that water managers should modify treatment to how they see fit. However, it is also important to note that "public water systems are not required to notify their customers of any bloom or cyanotoxin occurrence and are not required to include detections as part of a system's Consumer Confidence report."

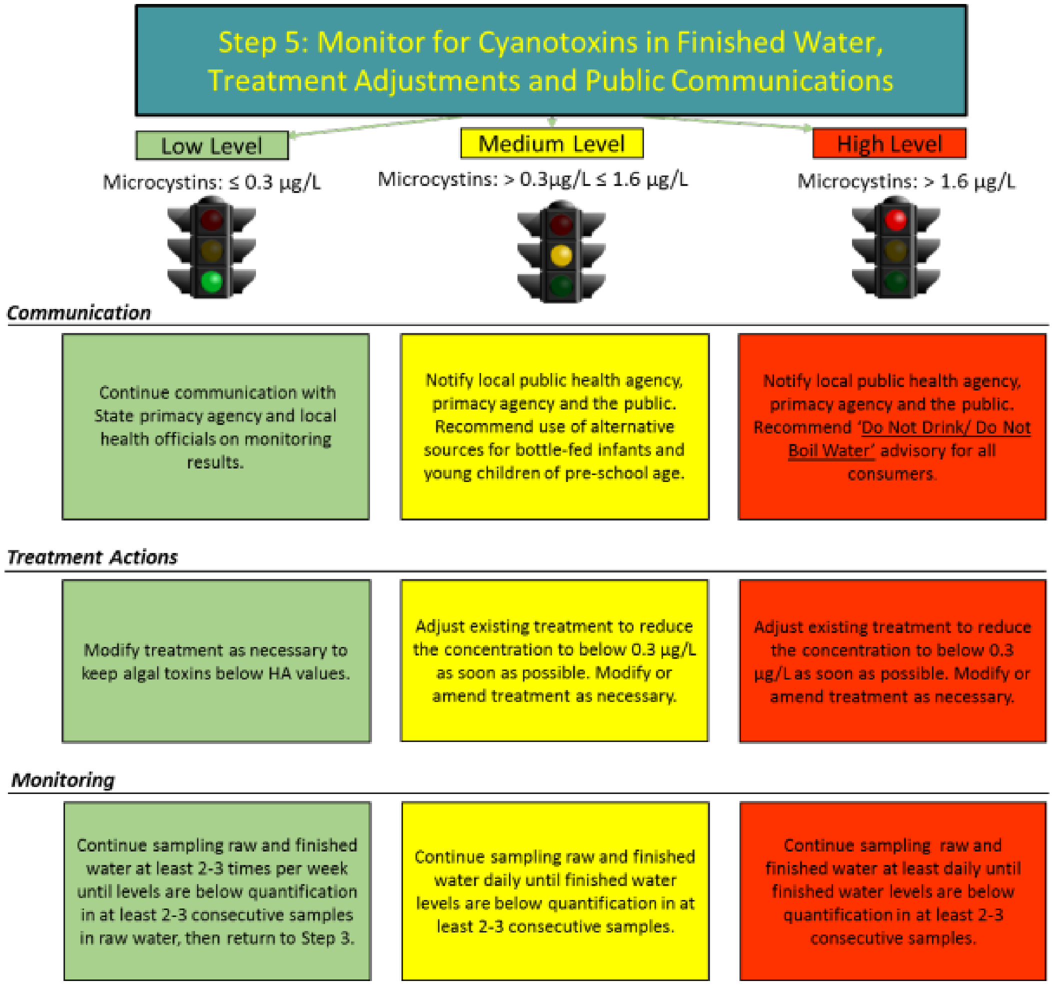

Figure 6. Traffic Light Approach

This is the Federal EPA's suggested response for water managers when cyanotoxins are present in finished water supplies. (Source: Recommendations for Public Water Systems to Manage Cyanotoxins in Drinking Water Accessed 01/25/2022)

4.0 Conclusions

HABs are a threat and nuisance to public health and the environment. They destroy the balance of ecosystems and cause damage that could last decades. The toxins cyanobacteria create affect numerous areas of the body that can cause acute and chronic effects that harm human and animal health. Even though HABs are increasing in frequency and duration they are not considered as serious of a threat because they are not a part of any federal regulations. Although health advisories are in place, they are not a substitute for a standard practice and guidelines that are legally enforceable. There is a great economic burden for the lack of preparation and understanding in dealing with blooms, especially those water management systems that have not dealt with them in the past or dealt with more severe blooms.

4.1 Current Problems and Necessary Changes

The *Recommendations for Public Water Systems to Manage Cyanotoxins in Drinking Water* is a good start to lay the framework in managing drinking water but misses the mark on addressing which treatments are best for certain scenarios and doesn't categorize at what concentration it is considered a difficult bloom to manage in raw water. Another thing the EPA does not address is public or recreational use of waters that may be contaminated with cyanotoxins.

The EPA suggests as part of the monitoring process, Step Two, to utilize three different indicators. The first is to do a visual inspection paired with phytoplankton identification, look at system effects, and lastly to search for other bloom indicators. However, a visual inspection is not the most reliable way to see if a cyanobacterial bloom is present. It does not tell the water manager if the bloom is producing toxins nor what type of toxin it is producing should the cyanobacteria have the capability to produce it. Also, a bloom could be present even if the standard characteristics of a bloom like discoloration, clarity, odor, and scum formation is not present. If water managers only visually inspect their water supplies, they may overlook a potential HAB and cause detrimental consequences later.

Adding phytoplankton monitoring along with visual inspection would help identify cyanobacteria presence even if visually it is not apparent. However, the EPA mentions that staff need to be trained on phytoplankton identification and does not list resources or ways to train the staff on this subject. It does not say if there is a certification required or if it is purely up to the water managers discretion on what trained means in determining phytoplankton species. However, Ohio's EPA has its own response strategy for HAB where it lists a reference to study and sample water that includes understanding phytoplankton's seasonality how to study it (DeWine et al, 2020). This guide created by Ohio's EPA also has a reporting center for the state listed where forms can be filled out to report on HAB so that the state government can better track and characterize future blooms (DeWine et al, 2020).

Ohio EPA went even further with their monitoring step by integrating quantitative polymerase chain reaction (qPCR) testing method into their guidance to help water managers identify how much cyanobacteria is present in the water supply (DeWine et al, 2020). It also allows the water manager to determine whether microcystins, cylindrospermopsin and/or saxitoxin is in the water. After the water management systems receive these results, they can get help interpreting next steps to take from the Ohio EPA (DeWine et al, 2020). This testing method is not utilized or mentioned in the EPA’s Recommendations document even though it is a helpful testing method and an integral part of Ohio EPA’s treatment process.

The federal EPA document lists some mitigation efforts that water systems can utilize like ultrasonic treatment, algaecides, coagulants, skimming, aeration, and mechanical mixing in Step Two (Recommendations, 2015). However, many of these treatments could cause more harm than help if the cyanobacteria contain intracellular toxins. The toxins could be released because of these treatments if the cells are lysed open through the process. A lot of these listed treatments are helpful even if they have drawbacks. But the biggest stipulation is that the toxin is not intracellular. Understanding whether the water supply has cyanobacteria that contain toxins intracellularly versus extracellularly is extremely pertinent. The biggest problem of the federal EPA recommendations document is that these mitigation efforts are mentioned in Step Two of the process, yet they mention the importance of knowing whether the cyanotoxin is intracellular or extracellular in Step Three. Because this is a step process, water managers may not look ahead to Step Three because they haven’t met the requirements to move on to the next step in the process for treatment.

The last major problem with the federal EPA’s recommendations document is the final step, Step Five. It is in respect to their traffic light approach, Figure 6 above, with the three levels, low level which is green, medium level categorized as yellow, and high level represented by red (Recommendations, 2015). It only separates these three levels based upon microcystin concentration. This does not include looking at other cyanotoxins like anatoxin, cylindrospermopsin and saxitoxins. Although monitoring mentioned before looked at visual inspection paired with phytoplankton identification, system effects, and searching for other bloom indicators, none of these aspects are included in the level indication for Step Five of the

Recommendations document. This final step of the process also does not help water managers determine a different course of action in the treatment process if they cannot successfully manage the microcystin level (Recommendations, 2015). Even though monitoring efforts are meant to help characterize the bloom in some capacity it is not utilized in this final step.

Ohio's guidance document however categorizes for water managers what characteristics are for minor, moderate, and severe blooms (DeWine et al, 2020). It mentions cyanobacteria cell count numbers, qPCR results, potential visual indicators, chlorophyll levels and biovolume as multiple characteristics to help understand just how severe a situation is (DeWine et al, 2020). Another importance is that Ohio's EPA lists cyanotoxin thresholds for microcystin, anatoxin, cylindrospermopsin, and saxitoxins and require their states water management systems adhere to these standards (DeWine et al, 2020).

The federal EPA recommendations document needs to be looked at again and revised to better lay out the process in treating water systems for water managers. More treatment options need to be added to the federal EPA's recommendations document. The NOAA was tasked to find new treatments and better understand HABs in 2014. Yet, numerous years have passed, and the Recommendations document has not been updated to reflect the science behind researching these events. Other studies are attempting to find alternative treatments, one including an alternative like utilizing microbial degradation of microcystin toxin (Dziga et al, 2013).

Ohio's guidance takes the foundation that the U.S. EPA's Recommendations document provides and creates an enhanced system. It is a better document to follow for water management systems since it contains more strategies, information, and clearer steps for managing HAB. After Ohio experienced its own HAB in 2014, they understood the importance of not letting such a crisis arise again. But this shouldn't be a reactive process for other states. States that utilize surface water sources for water management systems need to have their own specialized guidance to be prepared for when a HAB occurs.

All these factors push the need for the U.S. EPA to make cyanotoxins a contaminant under the SDWA. By doing this, a standardized method for managing HAB can be created and be enforceable. It will allow water management systems to cut down on the economic burdens HAB place on communities if management is already prepared and monitoring for blooms in the first place. HAB are only going to increase in frequency allowing more people to be potentially exposed to cyanotoxins in their drinking water. Its threat to environmental and human health is a credible problem now and even more so in the future. HAB are not just harmless phytoplankton that create discoloration in water systems. These small organisms can disrupt ecosystems and potable water systems. The U.S. EPA needs to make large changes if they are going to be able to effectively handle phytoplankton’s anticipated large influence in the future.

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